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FINAL TECHNICAL REPORT: WIDEBAND CONNECTIVITY AND SUPPORT FOR CRONUS CLUSTER AT USAF ELECTRONIC SYSTEMS DIVISION

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This final technical report describes the connection of a LAN-based Cronus Distributed Operating System Cluster at the USAF Electronic Systems Division to similar clusters at the Rome Air Development Center and at BBN via the DARPA Wideband Packet Satellite Network. Similar connectivity between ESD and the Jet Propulsion Laboratory, wide area network throughput measurement, performance studies, and network monitoring and control improvements are also described.

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1. INTRODUCTION

This Final Technical Report reviews the results of our support for the USAF Electronic Systems Division (ESD) in conducting the Technology Validation Experiment (TVE) over the DARPA Wideband Satellite Network. The ESD site in Bedford, MA contained computers running the Cronus Distributed Operating System, as did sites at the Rome Air Development Center (RADC) in Rome, NY and BBN Systems and Technologies Corporation in Cambridge, MA. The goal of the TVE is to demonstrate that a large computer-based simulation can be run in a distributed computation environment provided by Cronus Distributed Operating System "clusters" located at the ESD, RADC, and BBN testbeds. Relatively high-bandwidth data paths are required for the support of the simulation's wide area intercluster communications.

This contract provided for the support of the TVE at ESD. Major task areas included the provision of Wideband connectivity, on-going operational consulting and repair, analysis of data communication media and protocol performance, and monitoring and control services.

2. OVERVIEW OF PROBLEM AND OBJECTIVES

2.1. COMMUNICATION EQUIPMENT

The major task was to supply network connectivity among the Cronus machines at the three sites. Cronus machines on the Local Area Networks (LANs) at BBN already had connectivity with the Cronus machines at RADC's LAN via the existing Butterfly Internet Gateways and the DARPA Wideband Satellite Network. To add network connectivity with ESD Cronus hosts, a Butterfly Internet Gateway was procured for the ESD site. With a distance of several miles between the ESD site at Mitre Corporation in Bedford, Massachusetts and the nearest Wideband Earth Station at Lincoln Laboratory, a T1 (1.5 Mbits/sec) circuit was ordered to complete the communications paths.

Several months into the contract, the ESD site needed to relocate. ESD plans required moving the TVE SDI staff and equipment from the Mitre-B building in Bedford, MA to the Mitre-T building in Lexington, a distance of several miles, and actually closer to the Lincoln Laboratory Wideband site. This led to cancelling the T1 line and ordering a replacement line to the new building. The Butterfly Internet Gateway was moved, and re-installed on the appropriate ethernet in the Mitre-T building.

An independent task for network connections between the Jet Propulsion Laboratory (JPL) and ESD was added later in the contract period. The aim of the additional connectivity was to support SDI simulation work being conducted jointly between ESD and JPL. A high-bandwidth path between a JPL Hypercube multiprocessor and ESD Sun and Silicon Graphics Iris workstations was required. The ESD end required another ethernet interface card in the existing Butterfly Internet Gateway, plus the network cabling. The JPL end required another Butterfly Internet Gateway with local ethernet interface and cabling, plus an additional T1 circuit between JPL at Pasadena, CA and the nearest Wideband node at Information Sciences Institute (ISI) in Marina del Rey.

BBN took responsibility for coordinating installation, maintenance, and operation of the communication equipment supporting the Wideband usage by ESD.

2.2 PERFORMANCE ANALYSIS

With the Cronus TVE simulation, the performance of the network was critical to the elapsed time of an experiment. The project provided an opportunity to compare a distributed application in the LAN and WAN environments. We studied both the vendor-supplied network software and the underlying Cronus use of the available bandwidth. With data gained from the studies, a more flexible set of Cronus data-passing calls has been designed and is being implemented.

2.3 NETWORK MONITORING

Three monitoring changes evolved over the length of the contract. First, the Wideband monitoring and control software was ported from the C/70 host run by the NOC to a Sun workstation environment, which is more commonly available. Next, a Cronus application was developed which would give even a naive user a graphical picture of the communication components (BSATs and Gateways) and the Cronus hosts. Finally, a new Wideband Network Monitor was implemented as a prototype of a future graphical tool. It was built upon existing Automated Network Management (ANM) tools. The Cronus TVE work involved multiple network technologies, host system software, and host application programs. Monitoring and control in the resulting environment demands a clear display and an intuitive command structure.

3. METHODOLOGY AND TECHNICAL RESULTS

The initial ESD TVE experimentation began with a new high-speed wide-area connection established between an ESD testbed facility in Bedford, MA and testbeds at the Rome Air Development Center (RADC) in Rome, NY and at BBN Systems and Technologies Corporation (BBN) in Cambridge, MA. It is provided via a BBN Butterfly Internet Gateway that was installed at the ESD testbed, interfacing an Ethernet LAN at ESD to the DARPA Wideband Network via a terrestrial T1 circuit. The T1 circuit terminates at the gateway and at the Wideband Network packet switch node (known as a BSAT) at MIT Lincoln Laboratory in Lexington, MA. The Cronus/TVE cluster connectivity is shown in Figure 1.

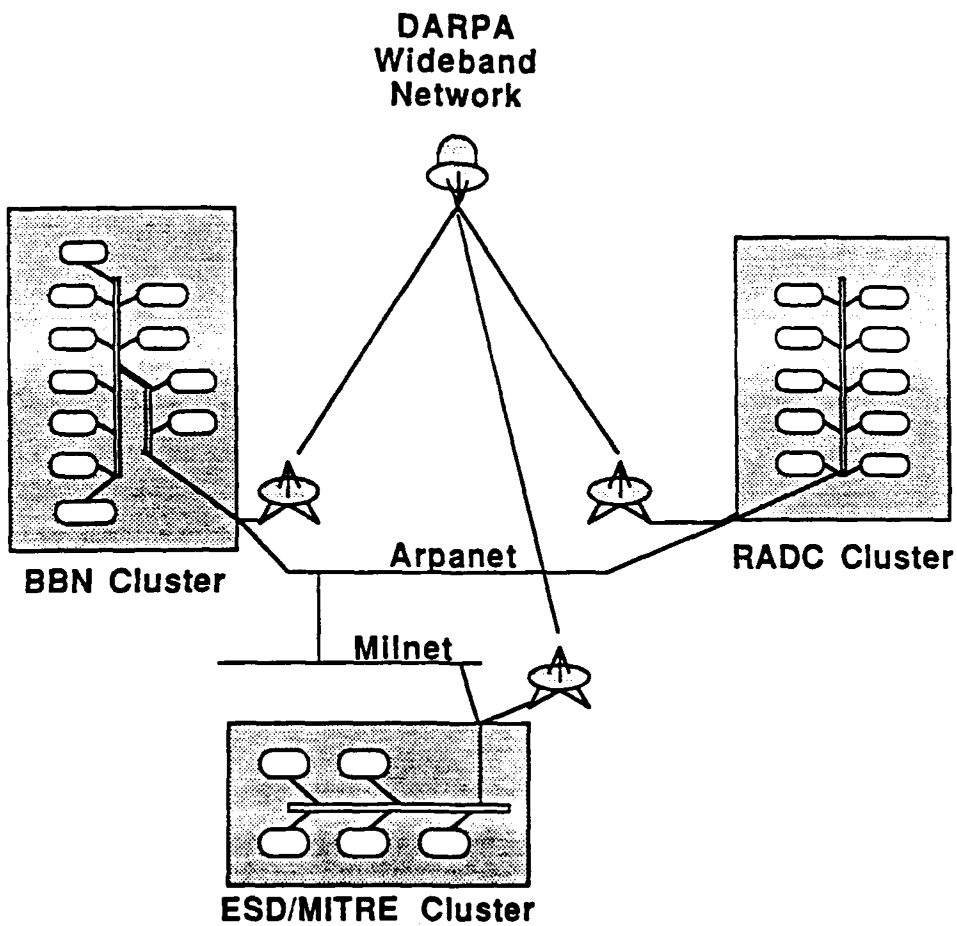

Figure 1. Cronus/TVE Cluster Connectivity

A number of engineering issues were addressed in the installation and initial use of the ESD Wideband Network connection. One of these was the determination of the most suitable link technology for the ESD-Lincoln T1-rate connection. A leased terrestrial T1 circuit was chosen, installed, and tested for this purpose in favor of the use of microwave link technology after a site survey revealed the lack of a clear line of sight between the ESD and Lincoln Laboratory facilities.

Other engineering issues related to both the provision of an Ethernet LAN for the ESD Cronus/TVE hosts and to the provision of ARPANET connectivity to the ESD site as a redundant backup path for enhanced TVE survivability. Since the ESD facility where the TVE hosts and Butterfly Gateway were to be located was found to be already equipped with an available Ethernet LAN (the MitreNet), a decision was made to home the hosts and gateway on that LAN rather than install a new dedicated Ethernet. The MitreNet connection also provides the advantage of backup connectivity to the RADC and BBN sites via a path other than the ESD Butterfly Gateway. Such backup connections are routed through a VAX host acting as an Internet gateway on the MitreNet to the DDN (Milnet) and from there to the ARPANET via a DDN mailbridge gateway. (Both the RADC and BBN TVE testbeds are equipped with ARPANET access via Butterfly Internet gateways.) Given the availability of this backup Internet path to the TVE hosts at ESD, a direct interface to the ARPANET was not installed on the ESD Butterfly Gateway as was originally planned.

The establishment of initial TCP connections between the TVE hosts at ESD and their counterparts at RADC and BBN required modifications to the ESD hosts' routing tables to use the ESD Butterfly Gateway as the favored path to the other sites. With the correct implementation of these routing table changes, ESD-RADC-BBN connectivity via the Wideband Network became routine. In general, the connections established via the Wideband Network have provided performance superior to connections established over

ARPANET paths. This is due to the high-speed nature of the Wideband path as well as to congestion frequently encountered within the ARPANET.

Due to access restrictions enforced between the ARPANET and Milnet communities of hosts, the Butterfly and VAX Gateways homed on the MitreNet do not exchange any Internet routing information. This restriction currently results in a requirement for manual ESD host routing table modifications when switching to the VAX-provided path upon a failure in some part of the Wideband path. Although there are TCP/IP hosts capable of automatic changeover capability, the standard Sun Unix and DEC VMS host software does not do this. Adding this enhancement is desirable for an operational Wide-Area Cronus cluster, but not necessary at this stage of use.

An opportunity for a test run of a wide-area distributed TVE simulation supported by the Wideband Network was provided at the December 1987 RADC Distributed Systems Technology Exchange Meeting. Although this test run was generally successful, it was limited to only the RADC and BBN Cronus clusters due to problems encountered with satellite channel connectivity at the Lincoln Laboratory Wideband Network site.

As the use of the distributed Cronus clusters became a reality, other overall ESD plans impacted the three site experiments. The ESD cluster and Butterfly Gateway were located in ESD facilities at Mitre-B Building in Bedford, MA. ESD needed to relocate the Cronus cluster to different facilities a number of miles away at Mitre-T Building in Lexington, MA in the early part of 1988. The Butterfly Gateway and the ESD termination point of the ESD-Lincoln T1 circuit had to be moved, and the gateway's connectivity to Lincoln Laboratory had to be established from the new location, in order to resume ESD's wide-area inter-cluster connectivity to RADC and BBN via the Wideband Network.

A tool was developed to periodically measure and record the end-to-end throughput achieved over TCP connections made between a Sun workstation host belonging to the

BBN Cronus/TVE cluster and a peer Sun host in the cluster at RADC. This tool automatically wakes up every six hours, creates the TCP connection, reliably transfers a megabyte of data over that connection, measures the effective throughput for the data transfer (excluding connection setup time where possible), and electronically mails the results to interested parties. A capability was developed to graphically display the resulting network throughput performance data sorted by either data transfer durations or by the time of day of the tests. This tool provides a "user" view of the wide-area communication layer performance that can be expected by the Cronus TVE application.

Performance data was continually collected using the measurement tool over an extended period. Although the measurement tool cannot directly determine the Internet path taken during a given data transfer (i.e., Wideband Network vs. ARPANET based paths), it does provide information on the initial Internet gateway used for the connection, from which the path may be inferred. The throughput performance of connections via the Wideband Network has been found to be relatively constant at about 16 Kbit/s, the maximum throughput to be expected given the standard SUN TCP window size and given the Wideband Network path's round trip delay.

An effort was initiated during the contract period to locate and correct the cause of unusually large intersite frequency offsets which were being observed on the Wideband Network's satellite channel; an overly large frequency distribution can result in degradations in satellite link performance which can adversely affect TVE performance. After investigation, the source of the problem was found to be incorrect adjustment of the synthesizers attached to the upconverters in the Wideband earth stations. BBN worked with Contel ASC, the Wideband earth station provider, to correct this problem the Wideband sites.

Problems encountered at the Lincoln Laboratory Wideband Network site which had prevented ESD's full participation in previous TVE test runs were corrected in January

1988. A bad IF cable connection within the Lincoln earth station, a likely contributor to the site's intermittent satellite channel connectivity, was repaired. In addition, a number of bugs were identified and corrected in the BSAT's processor node and channel I/O device software. Some of these bugs had been responsible for sporadic BSAT system-level restarts that were causing failures in TCP connections terminating at the ESD TVE hosts.

On February 17, 1988 the Wideband Network and Butterfly Internet Gateways provided the wide-area connectivity for a major demonstration of the TVE distributed simulation that was given by BBN Systems and Technologies Corporation to ESD. This successful demonstration included all three of the TVE sites: ESD, RADC, and BBN.

A Lincoln Laboratory Butterfly Internet gateway was installed in March 1988, directly connecting the Lincoln BSAT to the ARPANET, and creating additional backup path for the provision of wide-area TVE connectivity to ESD. This path provides ARPANET access in cases where there is an isolated failure in the Lincoln Wideband site's satellite channel subsystem (and all other communication subsystems remain operational).

As mentioned above, automated performance measurements show the throughput of intercluster connections routed via the Wideband Network to be relatively constant at about 16 Kbit/s. This result is a function of the standard TCP window size of 4096 bytes (32768 bits) used by the Sun workstations and the approximately 2 second end-to-end round trip delay characteristic of the Wideband Network path. The 2 second Wideband path round trip delay represents the sum of satellite channel propagation delays (two 1/4 second "hops" in each direction for Wideband Network datagram transmission => ~1 second of propagation delays), current Wideband distributed scheduling site synchronization delays (~1/3 second, round trip), and assorted buffering, queueing, and processing delays in the Butterfly gateways and BSATs. The round trip delay dominates the network transmission

rate in determining the maximum achievable TCP connection throughput over the Wideband path since the transmission time of a complete 4096-byte window of data is negligible compared to the round trip delay.

Experiments were performed to determine the best intercluster Wideband path throughput that could be achieved between Sun workstations via modifications to standard available versions of TCP. The experiments resulted in an increased throughput of approximately 64 Kbit/s. This result was achieved via integration of the latest Berkeley TCP release into the Sun UNIX kernel, with the TCP's window size optimized (increased) for the Wideband path. Known bugs in the Sun kernel prevented a throughput increase beyond 64 Kbit/s; such an increase would require an experimental improved version of TCP with special options and better flow control to solve the high-speed/high-delay network problem. Improvements along such lines could be addressed in the future if required by the TVE application.

New firmware was installed in the "Earth Station Interface" (ESI) satellite burst modem/codec units that provide satellite earth station connectivity at all of the Wideband Network sites, including Lincoln Laboratory, RADC, and BBN. The new software provides performance improvement in ESI processing of satellite channel bursts via the use of larger buffers and more available memory for burst data storage. The intent of this change was a decrease in the frequency of satellite channel connectivity and burst data lossage in the ESI under conditions of high channel traffic loads; this should improve the quality of wide-area TVE connections.

Due to facilities-related problems at Mitre-T Building, the installation of the re-homed T1 circuit providing connectivity from T Building to Lincoln Laboratory was not completed until mid-June 1988. When the installation was completed, BBN personnel began work on re-integrating the ESD Butterfly Gateway (moved from its previous Mitre-B Building location) with the Lincoln Laboratory BSAT and the ESD Cronus cluster's Ethernet LAN.

Several problems in the operation of the re-homed T1 circuit prevented the reestablishment of stable Wideband connectivity for ESD until July.

Two efforts were initiated in July 1988 with the goal of improving the operation and efficiency of the Cronus TVE when executing in a multi-cluster wide-area network environment such as is currently provided by the Wideband Network and the ARPANET/DDN. The goal of the first effort was to make Wideband Network monitoring data available within the Cronus system. This capability was developed by porting the Wideband Network monitoring system from its original BBN C/70 computer base to the Sun Workstation environment, and by implementing a Cronus front-end manager and display which allows Wideband status information to be integrated with other data currently available to Cronus users. The Wideband monitoring data are contained in a status file which defines the primary interface between the Cronus manager and the "satellite network poller" component of the Wideband monitoring software. Operators of the Cronus system and Cronus application processes can use this new view into the underlying network layer, enabling them to optimize inter-cluster communication decisions based on the information presented. Figure 2 is an example of a Cronus display integrating both Wideband node and Cronus host status information. The standard Wideband network monitoring displays were also also be ported to the Sun environment to ensure that network monitoring data will be available for diagnostic purposes even when the Cronus-based monitoring capabilities are not.

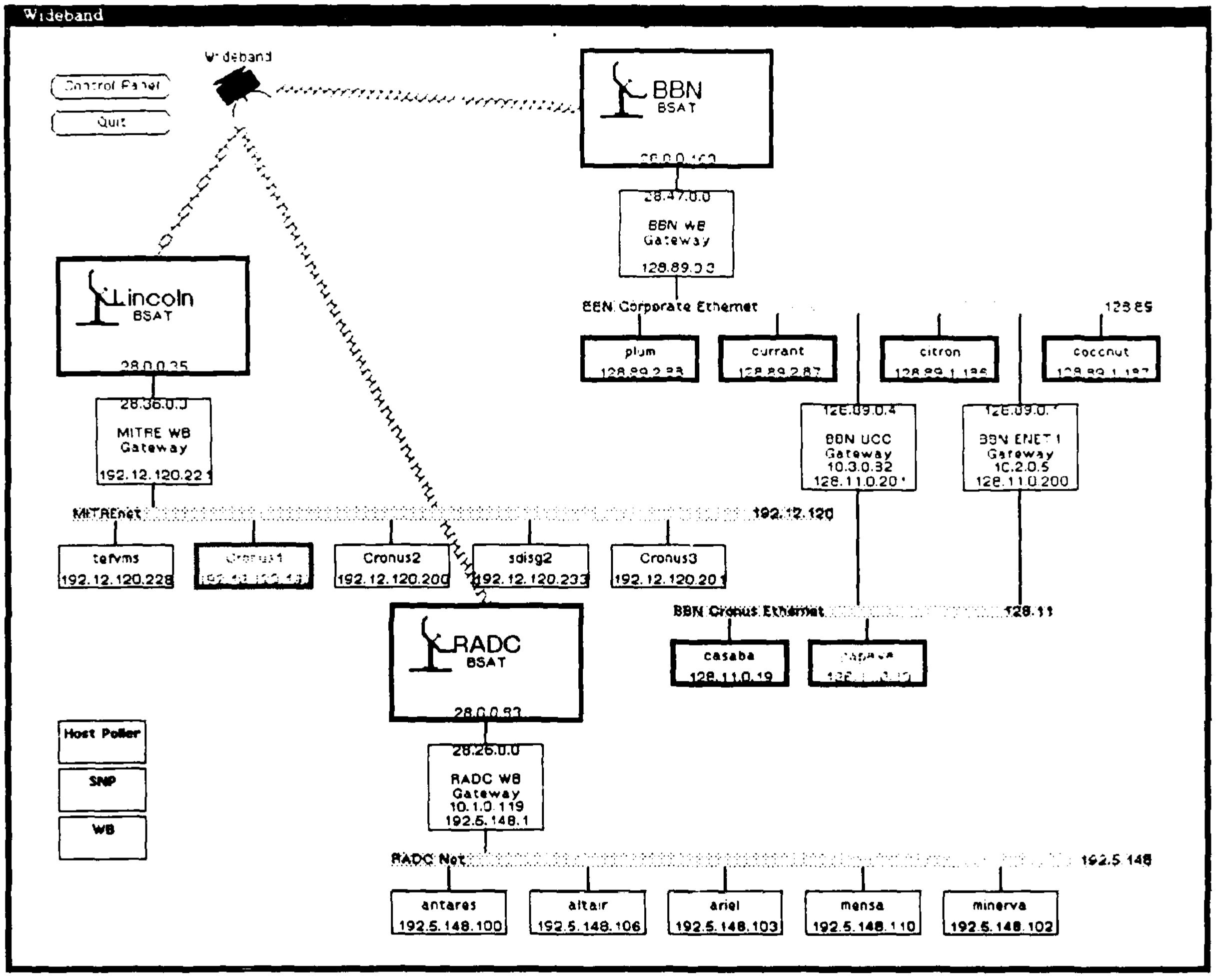

Figure 2. Cronus Display of Wideband Node and Host Status

The Cronus TVE operates by passing continuous streams of data between distributed computing resources. While this offers opportunities for concurrent processing through pipelined control strategies, such strategies had not been implemented. This is of particular significance in the TVE's wide-area networking environment, where Cronus' use of TCP/IP along with a synchronous invoke/reply protocol for each operation results in significant delays when data streams pass between remote sites. The second effort initiated was a design study on approaches to remedying this performance problem. This work involved consideration of various asynchronous and stream based protocols, including possible use of the existing ST protocol for high data rate applications.

A six month extension and modification of the work statement for this contract was

approved by the government on 26 August 1988. The work statement was expanded to provide for the connection of the Jet Propulsion Laboratory (JPL), located in Pasadena, CA, to the Wideband Network via the Wideband node at Information Sciences Institute (ISI), located in Marina del Rey, CA. This connection is part of a high-speed communication path for the support of distributed SDI simulation work being done at both JPL and ESD. The simulations run on a Hypercube multiprocessor hardware base and are accessible via Sun and Iris workstations. Full complements of all of these machines are currently installed on separate Ethernet LANs at the two sites.

The connection of JPL to the Wideband Network was completed in September. This work entailed the installation of a Butterfly Internet Gateway at JPL with interfaces to a local JPL Ethernet, and to the remote BSAT packet switch at ISI via a terrestrial T1 circuit. The completion of the JPL-to-ESD Wideband path also required the addition of a new interface to the ESD Butterfly Internet Gateway to connect the local "ESD-Hypercube" Ethernet to the Wideband Network.

The use of Cronus on the Wideband network was presented at RADC COTD demonstrations during December 1988 and January 1989. Both presentations were conducted at RADC using the Wideband Network to connect the RADC network to resources at BBN. The December demonstration was for RADC personnel. The January demonstration was part of the RADC COTD Technology Exchange Meeting, attended by other COTD contractors. Demonstrations included the Cronus TVE simulation software, the monitoring and control services (both Sun-based Wideband Network monitoring and also distributed system service monitoring tools supported by Cronus) and distributed remote database services. Most all demonstrations illustrated use of the Wideband Network for resource sharing between RADC and BBN.

The design of a strategy for asynchronous request mechanisms in Cronus and of

enhancements to their TCP connection management mechanisms was completed in December 1988. This work was recommended earlier by performance studies on the TVE which indicated that the long round-trip delays on the Wideband network would impact performance of synchronous interactions and of certain uses of TCP connections common to the TVE simulation software. The design notes were referred to the Cronus group for review. The asynchronous mechanisms, which offer performance improvements in the TVE and several other applications, regardless of network technology, were incorporated into Cronus and will be supported in their next release. The connection management mechanisms, which are more complex, are planned for implementation for release mid 1989.

As a final task, the Sun-based Wideband monitoring capability was carried further into a window-based graphical system by leveraging off functionality already existing within the Automated Network Management (ANM) system. Using a packet radio monitoring module as a starting point, a prototype Wideband Network monitoring tool was built. Complementing the Cronus monitoring program which displays Cronus component status, this Wideband Network monitoring tool probes into the Wideband components for the detailed status available there.

The Automated Network Management system is a DARPA- developed network management system based on distributed components connected via a common protocol. This commonality allows users to add new components into the system and thereby take advantage of ANM's already existing functionality. Some features of ANM that would be of use for monitoring any network are graphical color displays representing network status and the capability of adding intelligent trouble shooting client applications to the system.

The goal of integrating the Wideband Network monitoring into the ANM structure is to provide to the network the capabilities of the ANM system, thus further enhancing the

management of the Cronus/TVE's underlying networking substrate. This integration was accomplished by creating an intermediate process to translate between the ANM information format and the format used by the existing Wideband monitor. The translator receives reports from the Wideband monitor and sends repackaged monitoring information to the current ANM management module. Other processes, such as the Integrated Monitoring display process, can then access the management module for status and performance information from the Wideband Network. The translator and Wideband monitor were not changed to take advantage of all of the possible ANM capabilities. Only the basic network status reports are sent to the ANM management module. Also, an already existing view for a packet radio network was used to display the status of the Wideband Network. The result, however, is a graphical display which can quickly tell an operator if any Wideband site is not functioning properly.

4. CONCLUSIONS

The execution of the TVE simulation among the three Cronus clusters did put some stress on the Wideband Packet Satellite Network and on the Butterfly Internet Gateways. The Cronus TCP/IP traffic during long simulations involving several hosts helped uncover some Wideband problems, since it exercised the paths and protocols differently than, for instance, the stream protocols used in video conferencing. The Wideband support group analyzed and corrected several problems that a "real-world" application could help uncover.

The Cronus project, with considerable experience in host-host communication on a local Ethernet, benefited from the study of an application run among hosts with larger communication delays. Our study of the Sun TCP/IP performance helped our understanding of how much can be expected from vendor-supplied operating system software when used in configurations beyond a single LAN. The study of the standard Cronus synchronous invoke/reply operation protocol has provoked a re-design of the basic mechanism. Future Cronus releases will have more flexible options, resulting in higher effective bandwidth for applications with larger data flow.

Both the installation of the physical equipment responsible for the ESD Cronus cluster, and the on-going support were major tasks. In performing these tasks, both the Cronus TVE simulation users and the network support groups discovered that network monitoring functions needed improvement. Benefits are gained wherever a user can both find out if all multi-network components are reachable, and can focus in on the performance of a single network piece. The monitoring tools tested during this contract should lead to better, more permanent monitoring and control strategies.

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